RESEARCH DEPARTMENT

Compatible single-sideband modulation experimental investigation of the performance with conventional a.m. receivers

RESEARCH REPORT No. G-100

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THE BRITISH BROADCASTING CORPORATION
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RESEARCH DEPARTMENT

COMPATIBLE SINGLE-SIDEBAND MODULATION: EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE WITH CONVENTIONAL A.M. RECEIVERS

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for Head of Research Department

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COMPATIBLE SINGLE-SIDEBAND MODULATION: EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE WITH CONVENTIONAL A.M. RECEIVERS

SUMMARY

A laboratory investigation is described of the overall performance of a compatible single sideband (c.s.s.b.) system when used with current types of domestic receivers. The system employs an alternative method of amplitude modulation to that normally used in the l.f., m.f. and h.f. broadcasting bands, the sideband on one side of the carrier being largely suppressed. Audio quality, performance under fading conditions, co-channel and adjacent-channel interference were all measured.

In general, c.s.s.b. showed very little difference in performance from conventional double-sideband amplitude modulation. With existing receivers a significant difference was found only for adjacent-channel interference, when either an advantage or a disadvantage could arise depending on the symmetry of the suppressed sidebands of the transmissions.

1. INTRODUCTION

The first form of carrier modulation used for broadcast transmissions was amplitude modulation and this form of modulation has remained in widespread use ever since in the low frequency (l.f.), medium frequency (m.f.) and high frequency (h.f.) broadcast bands. The development of broadcasting has led to a large increase in the number of transmitters so that there is considerable overcrowding in the broadcast bands. Means of reducing the radio frequency (r.f.) bandwidth of each transmitter have been sought and, in particular, as normal double-sideband amplitude modulation (d.s.b.) produces two "identical" sidebands, other amplitude modulation systems have been used which transmit only one sideband - thus halving the r.f. bandwidth required. These methods have not been used in the broadcast bands because special receivers are required to give distortion-free reception. In recent years there have been proposals[1,2,3,4] to use a signal with the bandwidth of single-sideband modulation but the envelope of d.s.b. In principle, such a signal (known as compatible single sideband (c.s.s.b.)) could be received on normal d.s.b. receivers without distortion.

There seems to be no doubt that c.s.s.b. would provide many advantages over d.s.b. if ideal receivers were used. If, however, it is to be regarded as a compatible system, that is, one which can be received with existing receivers, some limitation in performance may be expected because of the receiver characteristics. As there is no convenient method of predicting the subjective effect of this degradation, subjective tests were carried out with two domestic receivers, one using transistors and the other valves. Throughout the tests emphasis was placed on the compatibility of c.s.s.b., its performance being assessed by comparison with d.s.b.

All the subjective tests were carried out with programme material recorded from the lines feeding normal broadcast transmitters and the programmes were chosen to represent typical broadcasts.

Section 2 considers the theoretical properties of c.s.s.b. and Sections 4 to 8 give the results of the laboratory tests. A comparison with the results of full-scale field trials which have been carried out[5] is given in Section 9.

2. COMPATIBLE SINGLE–SIDEBAND SYSTEMS

The fundamental problem in c.s.s.b. is to generate a single–sideband signal whose modulating waveform can be recovered without distortion from an envelope detector. There are two approaches to this problem: in the first the a.f. input to a carrier-plus-single-sideband transmitter may be predistorted so that the output from an envelope detector is un-

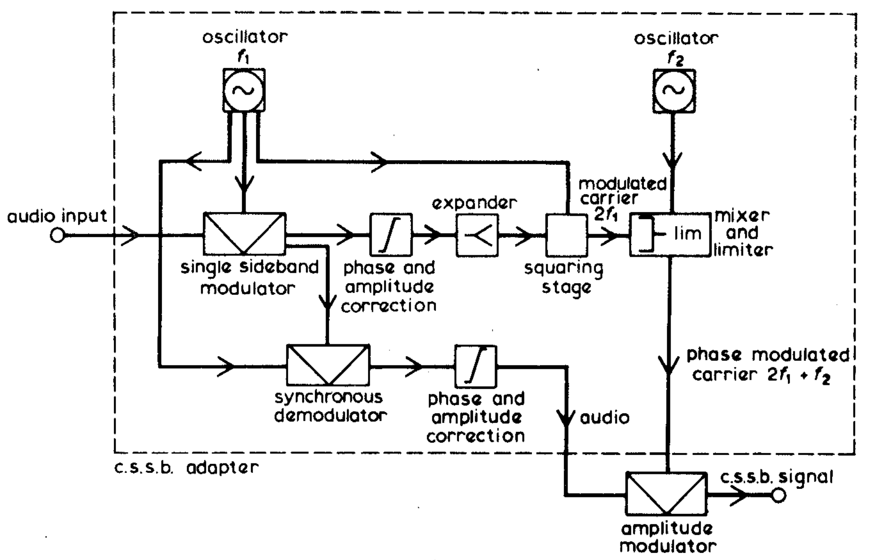

Fig. 1 - Block diagram of c.s.s.b. generator

distorted. Secondly the carrier frequency drive to a conventional d.s.b. transmitter may be phase modulated in such a manner that the spectrum is one-sided. Up till now only the second method has been used in practice.

The first practical solution to the problem of generating a c.s.s.b. signal was described by Kahn[1] who later gave an improved version.[2] An alternative method (known as the squaring method) has been described by Van Kessel and others[3,4] and the modulator used in the present series of tests was of this type.

2.1. The "Squaring" Method of Producing C.S.S.B.

Fig. 1 shows a block diagram of a c.s.s.b. modulator. It consists of a normal amplitude modulator and a c.s.s.b. adapter shown enclosed by the dashed line. The adapter is housed in a single box measuring 440 mm × 220 mm × 135 mm. The method of operation depends on squaring a single-sideband signal, together with a suitable fixed-carrier component, and then filtering and limiting the output signal in the region of twice the original carrier frequency. This signal is used, after a suitable frequency change, as the phase modulated drive for a d.s.b. transmitter which, in the laboratory generator, is represented by the amplitude modulator. It is essential to keep the phase and amplitude modulations in step. This is facilitated by deriving the a.f. input to the final amplitude modulator by synchronous demodulation of the single-sideband signal formed in the adapter, thus ensuring that the phase and amplitude characteristics of the single-sideband modulator do not require compensation. Amplitude and phase controls are provided after this stage in order to allow for the individual characteristics of the transmitter amplifying stages and the final modulator. An expander in the phase-modulation path improves the sideband suppression at high modulation depths.[4]

Because the final stage in the generation of the c.s.s.b. wave is an amplitude modulator, the envelope is exactly the same as it is for normal d.s.b. (assuming that the r.f. bandwidth of the transmitter is sufficiently large, as is usually the case). Significant power in the r.f. spectrum occurs only to one side of the carrier, but may extend to a frequency whose spacing from the carrier exceeds the maximum audio frequency, particularly if large modulation components near the upper-frequency limit are present. Provided that no single component of audio frequency greater than 4 kc/s has an amplitude of more than 30%, the spectrum is effectively confined to 8 kc/s on one side of the carrier. The modulation waveforms which occur in normal broadcasting almost always meet these requirements.

2.2. Advantages and Disadvantages of C.S.S.B.

When discussing c.s.s.b. and d.s.b. it is convenient to use the conventional representation shown in Fig. 2. The d.s.b. signal extends on

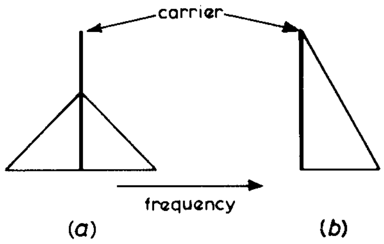

Fig. 2 - Representation of (a) d.s.b. signal and (b) c.s.s.b. signal

either side of the carrier (denoted by the thick vertical line) to the maximum audio frequency while the c.s.s.b. signal extends to the same frequency on one side only. The height of the c.s.s.b. triangle is twice the height of the d.s.b. triangle to indicate the greater spectral power density needed to ensure that the detected audio voltages will be the same in the two cases.

As nearly all m.f. and h.f. receivers have i.f. bandwidths which are considerably less than the transmitter bandwidth, only this case is considered here. Fig. 3 shows the two signals in relation to an ideal (phase linear) intermediate frequency (i.f.) amplifier. If an i.f. bandwidth $2B$ is used for d.s.b. as shown in Fig. 3(*a*), the i.f. bandwidth required to give the same audio bandwidth with c.s.s.b. is only B as shown in Fig. 3(*b*). Apart from the possibility of distortion discussed later, the detected audio voltage is the same for each system but the noise power in the c.s.s.b. case has been halved; hence there is a 3 dB improvement in signal-to-noise ratio. If the i.f. amplifier is not reduced in bandwidth then it is possible to have a wider modulation-frequency bandwidth for c.s.s.b. as shown in Fig. 3(*c*) for the same signal-to-noise ratio as in d.s.b. As the selectivity of the i.f. amplifier is the main cause of loss of the upper audio frequencies in typical m.f. receivers, this could be a very useful advantage where receiving conditions are suitable.

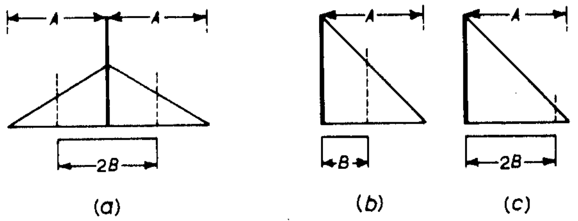

Fig. 3 - I.F. passband in relation to d.s.b. and c.s.s.b. signals

A is the maximum transmitter audio frequency
B is the maximum audio frequency received in case (*a*)

Practical i.f. amplifiers have response/frequency characteristics whose sides are not infinitely steep and thus signals in channels adjacent to the wanted signal channel cause interference: c.s.s.b. may be expected to provide less interference in some situations. Figs. 4(*a*) and (*b*) show two of the most favourable possibilities while Fig. 4(*c*) shows one where there will be more interference from a c.s.s.b. rather than a d.s.b. transmission because with c.s.s.b. there is more energy in the interfering sideband which is nearer to the wanted signal. If there is sufficient advantage when conditions are favourable it may be possible to re-allocate transmitter frequencies and powers to reduce interference or, possibly, increase the number of transmitters.

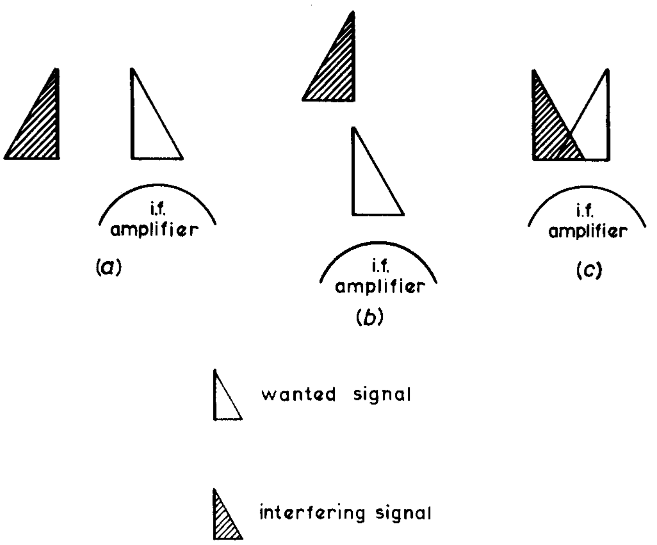

Fig. 4 - Diagrammatic representation of some interference problems

(*a*) Adjacent channel : most favourable case
(*b*) Co-channel : most favourable case
(*c*) Adjacent channel : least favourable case

It has already been noted that an improvement in signal-to-noise ratio or an improvement in effective audio bandwidth may be expected with c.s.s.b. However, when practical i.f. amplifiers are considered it is evident that the relative phases and amplitudes of the side-frequency components will be altered and this will cause distortion in the audio frequency output. Although it is possible to calculate and measure such products it is not easy to estimate the subjective effect because the distortion does not correspond to any of the well-known types of non-linearity. The experiments described in Section 4 therefore included subjective observations.

It has been claimed[2] that c.s.s.b. will give improved reception in fading conditions but theoretical analysis is very difficult. Some evidence on this point can be gained from the field trials described in Section 10 but more detailed laboratory experiments were also carried out under controlled conditions. These tests are described in Section 8.

3. EXPERIMENTAL METHOD

Objective tests were carried out by conventional methods but the subjective tests were arranged as "factorial" experiments and the results were evaluated using variance statistics. These methods, although widely used in such fields as biochemistry and agriculture, are rarely used in physics and engineering. A brief outline of the principles is therefore given in the following sections. More detailed descriptions are given in the References 6,7,8.

3.1. Factorial Experiments

Consider the situation when one subject is presented with a particular set of conditions and required to make some measurement. If he makes only one measurement then no knowledge is gained about the repeatability of the measurement, nor about what would happen if any of the conditions were changed, nor what would happen if a different subject were used. There are many ways of repeating the measurement to obtain this information but a "factorial" experiment represents the most efficient way of doing so.

In a factorial experiment the factors which are thought to affect the measurement are each given a number of values and then every possible combination of these values is measured. The factors are usually denoted by capital letters. Thus, if A is given five values, B two values and C three values, there are thirty different conditions, each of which is measured. From these thirty measurements the effects of A, B and C may be found and also the second and higher-order interactions:* AB, BC, AC and ABC. With appropriate analysis, every measurement contributes to every conclusion, so that the experiment makes very efficient use of the measurements. Very few repetitions (say two or three) are required to estimate the repeatability to a very high accuracy. For example, if each measurement is repeated only once then the estimate of error in each measurement is as good as it would be if any one measurement had been repeated about thirty times.

In most of the experiments described in this report, each factor is measured at only two levels. This does however permit a reduction in the size of the experiment when there is a large number of factors. For example, if there are five factors each of which can have two values, the total number of measurements is thirty-two. These measurements may be combined to give the mean, five primary factors, ten second-order factors, ten third-order factors, five fourth-order factors and one fifth-order factor. If it can be assumed (in this example) that all the third- and higher-order interactions are zero, then it is necessary to measure only one half of the total number of conditions in order to determine the mean, primary and second order factors unambiguously.

As the effect of using different subjects was also of interest, a number of subjects each did the complete set of measurements once. This provided a measure of the variation between subjects and also a measure of the repeatability of the experiment.

3.2. Analysis of Variance

A particular statistical method called Analysis of Variance has been developed for the analysis of factorial experiments. This method splits the total variation in the measurements into the variation caused by the factors (of all orders), the variation caused by the subjects and the remaining "random" or "error" variation which gives a measure of the repeatability of the experiment. The subject and factor variations are then tested for significance by comparing them with the error variation.

Analysis of Variance is rigorous only when the error variations form a normal population but in practice large departures from normality can be tolerated before the significance tests become invalid. In cases of doubt the appropriate statistical tests were made to assess this effect and if necessary some reserve was placed on the conclusions.

4. AUDIO-FREQUENCY QUALITY TESTS

It has already been pointed out in Section 2.2 that c.s.s.b. is likely to suffer from distortion in the detected signal because of the receiver i.f. selectivity. On the other hand it is possible to obtain a wider a.f. bandwidth than would be obtained with d.s.b. and the same i.f. amplifier. Objective measurements (described in Section 4.1) were carried out to assess the magnitudes of these effects in typical domestic receivers. An overall judgement can be made only by subjective measurements, however, and these are described in Section 4.2.

4.1. Objective Distortion Measurements

Fig. 5 shows the arrangement used for the objective distortion measurements, which excluded the effects of the receiver audio stages, but included the effect of the detectors. The distortion analyser[9] could measure the fundamental output or any of the harmonics or intermodulation products as a continuous function of frequency. The audio input

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* For example, the symbol AB stands for the second-order interaction between A and B and gives a measure of the effect that changes in B have on the results produced by changes in A. It should be noted that letters are used as a shorthand and the combination of letters does not indicate a product in the mathematical sense.

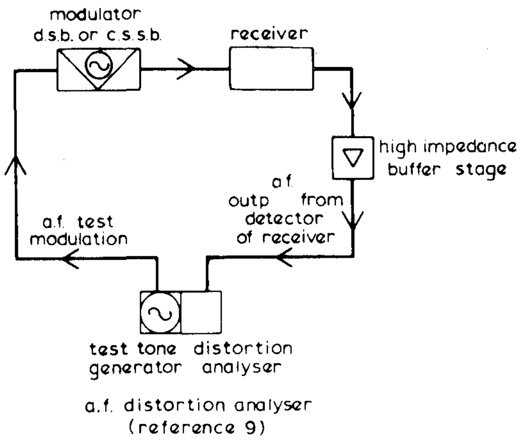

Fig. 5 - Arrangement for making objective distortion measurements

for the intermodulation tests consisted of two tones spaced 121 c/s apart (the lower being regarded as the "fundamental") each of amplitude m/2 where m is the nominal modulation depth. Measurements were made with both the domestic receivers and with both the modulation systems (c.s.s.b. and d.s.b.). The receivers were tuned either to the carrier or to +3 kc/s with respect to it (that is towards the wanted sideband for c.s.s.b.).

Figs. 6 and 7 show a few of the most significant results obtained. It may be noted that with c.s.s.b. the curves for the fundamental modulation frequency rise above the corresponding curves for d.s.b. at low frequencies. This relatively small effect is caused by circuits within the c.s.s.b. adapter but is not inherent in c.s.s.b. systems. With the receivers adjusted to the d.s.b. tuning point (Figs. 6(*a*) and 7(*a*)) the fundamental audio response is very similar for the two systems as may be expected if the i.f. responses are reasonably symmetrical. There is, however, much more distortion with c.s.s.b. When the receivers are detuned there is an improvement in the effective audio bandwidth, the increase measured to the -6 dB point being between 60 and 100% for c.s.s.b. and between 20 and 50% for d.s.b. Although Figs. 6 and 7 give only two samples of measurements, the trend was similar in the other measurements.

4.2. Subjective Tests

In the arrangement for the subjective quality tests a switch-key held by the subject provided an instantaneous change from one modulation system to the other. The subjects were not told which modulation systems corresponded with the key positions; also the positions were interchanged according to a "random" sequence.

The subjects were asked to switch from one position to the other until they could say which position (if either) gave the better quality. If a difference was found they were asked to say which of the following grades applied:

Slightly better	(1)
Better	(2)
Very much better	(3)

The numbers in brackets were scored for each grade, the sign being plus when c.s.s.b. was preferred and minus when d.s.b. was preferred.

The results of the experiment gave an overall mean value of -1·1 grades which shows that on average the subjects thought d.s.b. slightly better than c.s.s.b. This result was not affected by any of the four factors tested (programme, audio compression, receiver and tuning point) nor by any second-order or higher-order interactions. It was found that there was no significant variation among the subjects.

It may be concluded that the subjective effect of the increased distortion on c.s.s.b. would just outweigh the advantage of the increased effective audio bandwidth because the results were equally valid for the receivers in the detuned position. It should be noted, however, that this test was a sensitive one as it was carried out in good listening conditions by technical personnel accustomed to making such judgements. It is believed that non-technical subjects would not have felt there was a significant difference in quality between the modulation systems, but this conclusion was not specifically tested.

5. EXPERIMENTS ON RECEIVER TUNING

In some situations, the benefits which should arise from the use of c.s.s.b. depend on the listener's ability to tune the receiver to some particular point in the spectrum. It was therefore felt that some measurements should be carried out with non-technical subjects to find out just what they would do when asked to tune to a c.s.s.b. signal.

Each series of measurements was carried out with the arrangement shown in Fig. 8. The subject first listened to a short length of programme so that the station could be identified. The receiver was then detuned by about 50 kc/s and the subject was asked to retune to the required programme; the local-oscillator frequency was measured and the sequence repeated with a new set of conditions.

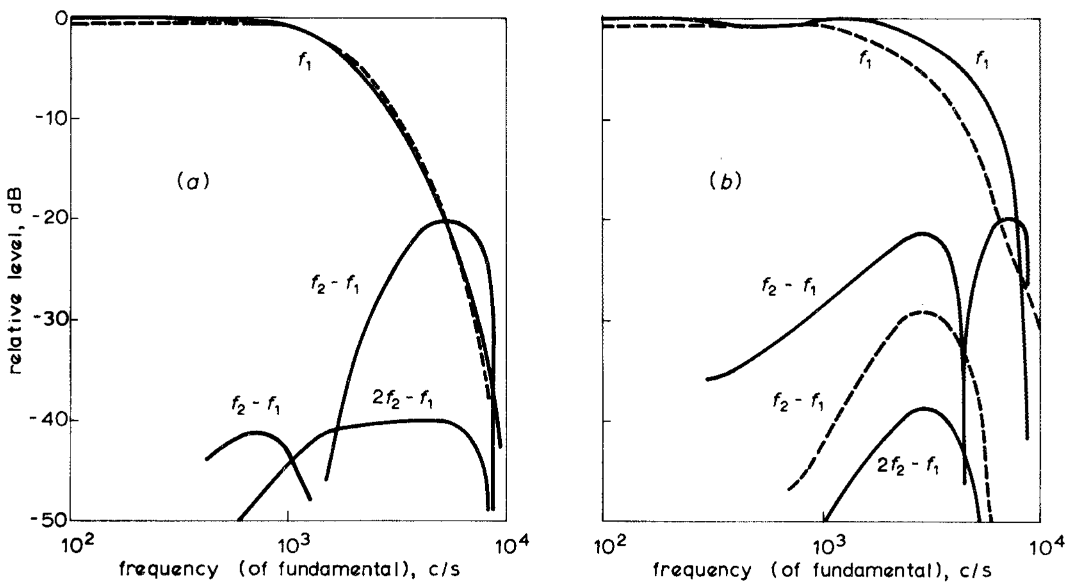

Fig. 6 - Objective measurements of intermodulation distortion : valve receiver, 90% modulation depth. The d.s.b. intermodulation products in (a) did not rise above -50 dB.

(*a*) no detuning (*b*) +3 kc/s detuning —— c.s.s.b. ---- d.s.b.

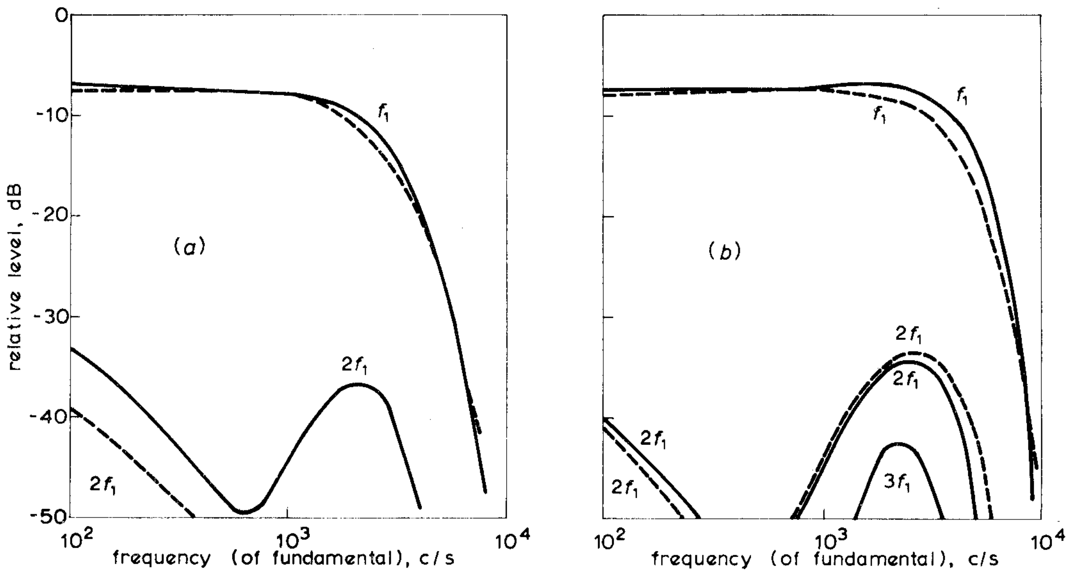

Fig. 7 - Objective measurements of harmonic distortion : transistor receiver, 40% modulation depth

(*a*) no detuning (*b*) +3 kc/s detuning —— c.s.s.b. ---- d.s.b.

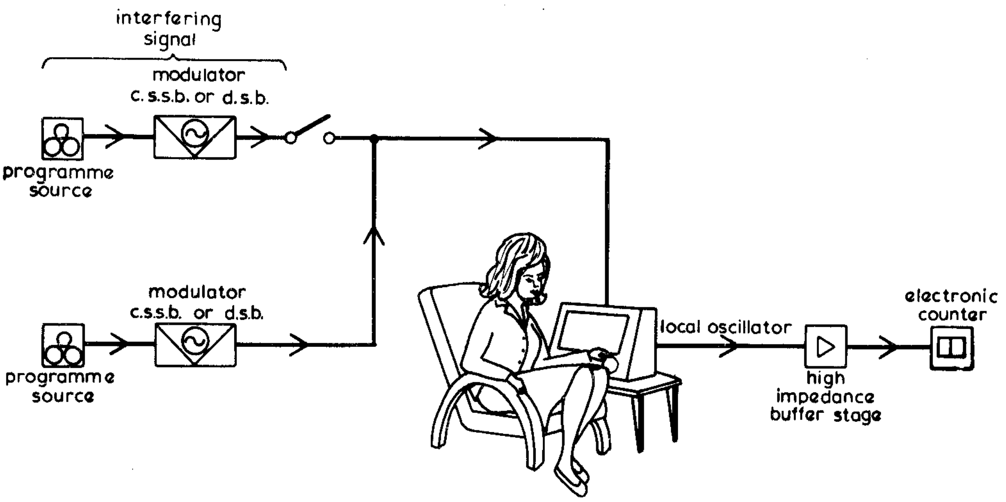

Fig. 8 - Arrangement for tuning tests

Two series of measurements were carried out, each with ten non-technical subjects, who were all women secretaries and tracers whose ages and musical interests were, as far as could be judged, reasonably representative of the U.K. population in general. Some listened to sound broadcasts very little while others listened regularly; m.f. receivers were used (at home) more often than v.h.f. receivers.

The possible advantages of c.s.s.b. and the unsymmetrical tuning characteristic were not explained to the subjects because it is thought that, in practice, a large fraction of the population would not be able to use this information to advantage. Some care was taken to make the programme reasonably interesting and, in particular, each subject was given the type of musical programme to which she said she frequently listened. Each subject was also asked to tune the receivers "as she would at home" as it was desirable to avoid a special effort on the part of the subjects.

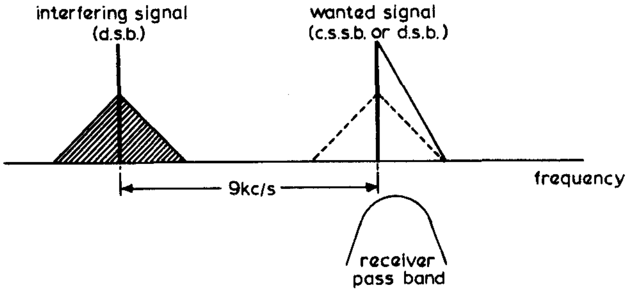

Fig. 9 - Schematic of the signals present in the first tuning experiment

5.1. The Tuning Point in the Absence of Interference and also in the Presence of Adjacent-Channel Interference

In the first experiment, the tuning point was measured for both c.s.s.b. and d.s.b. wanted signals, with and without interference. The interfering signal was a modulated d.s.b. signal spaced 9 kc/s away as shown in Fig. 9 and at a level of -8 dB with respect to the wanted signal. It can be seen from Fig. 9 that the interfering signal is placed on the lower-frequency side which would be expected to be more favourable to c.s.s.b. because the subjects could tune away from the interference and yet hear the wanted programme with reasonable quality.

The results of this experiment show first that, when there is no interference, the average tuning point is not affected by the modulation system and secondly that, when there is adjacent-channel interference, the subjects tuned away from the interference by the same amount (about 1 kc/s on average) for c.s.s.b. as for d.s.b. The other factors tested (receiver, signal strength, programme and audio compression) did not significantly change the tuning point.

One of the most interesting aspects of this experiment is the spread in the tuning points as measured by the value of the Standard Error (1·35 kc/s). This means that, if repeated measurements are made with one subject with any particular set of conditions, 95% of these measurements would be expected to lie within ± 2·67 kc/s of the mean. In other words, during an infinite number of tests, there would be a tuning error of about 2·7 kc/s or more one in twenty times. The possible tuning errors are therefore quite large and are comparable with the half-bandwidth of the i.f. amplifier. It might be expected that this result is unrepresentative because the subjects would find it more difficult to tune to c.s.s.b. than to d.s.b. but when the Standard Error for the c.s.s.b. measurements was compared with that for the d.s.b. measurements it was found that they were not significantly different. (The test was sufficiently sensitive to detect a 25% difference in the Standard Errors.) There is thus some evidence that the subjects found it equally difficult to tune to the two systems or, possibly, that they subconsciously made a greater effort when tuning to c.s.s.b.

5.2. The Tuning Point in the Presence of Co-Channel Interference

In carrying out the first series of measurements, the direction from which the subject had to tune into the wanted signal was "randomized". It was later realized that the direction might have a measurable effect on the final tuning point and so this was made one of the factors in the second series of measurements which was designed to find the effect of co-channel interference on tuning. The wanted signal was either c.s.s.b. or d.s.b. and the unwanted signal was also either c.s.s.b. or d.s.b., the c.s.s.b. signal being of the "opposite hand" as shown in Fig. 10.

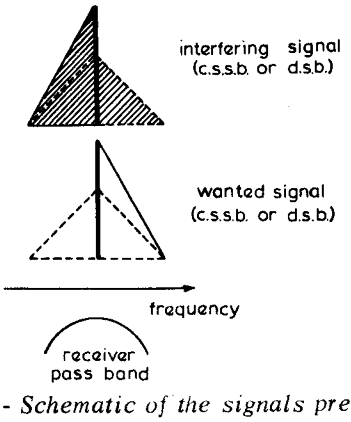

Fig. 10 - Schematic of the signals present in the second tuning experiment

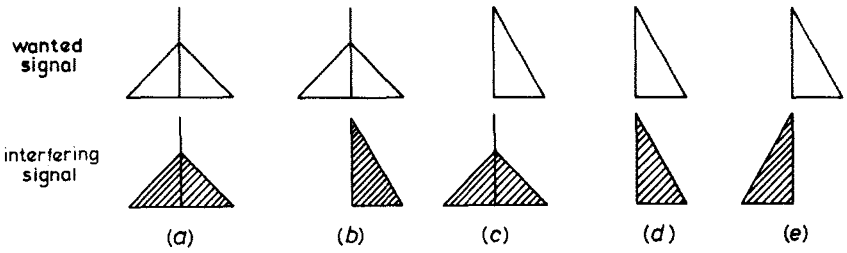

Fig. 11 - Five possible arrangements for co-channel interference

The results showed that none of the factors in the experiment had a measurable effect and it may be said that the subjects either could not or would not detune when it might have been beneficial to do so. Inspection of the individual results provided some evidence that some of the subjects tended to leave the receiver detuned about 500 c/s to the side from which the wanted signal had been approached, but the evidence was not very conclusive. The Standard Error was, however, significantly higher (34%) than in the first experiment implying that the subjects had greater difficulty in tuning in the presence of co-channel interference. The Standard Error was again not significantly different for the two systems implying that the subjects found them equally difficult to tune.

It has been suggested[2] that listeners who live in fringe areas and who are therefore accustomed to tuning to "difficult" signals will be better able to tune to c.s.s.b. and thus the improvement will be gained where it is most needed. Three of the subjects who took part in the above tests said they frequently listened to poor m.f. signals but the results for these subjects were not found to be significantly different from the remainder.

The results of all the above measurements may be summarized by saying that the tuning points for c.s.s.b. and d.s.b. are substantially the same and that, on the average, listeners tune the receivers so that the carrier is in the middle of the i.f. passband unless there is adjacent channel interference in which case they detune away from the interference.

6. CO-CHANNEL INTERFERENCE

The ratio between the carrier levels of a wanted signal and an interfering signal which produces a given grade of interference is known as the protection ratio required for that grade of interference. The protection ratios required for co-channel interference were measured subjectively using technical personnel. In this context co-channel was taken to mean the situation where the difference between the carrier frequencies was less than about 20 c/s. In the experiments the carrier frequencies were either derived from a common generator (thus in constant phase relation, or "phased") or were made equal to within 20 c/s ("non-phased").

Each subject first listened to the wanted signal without interference. The interfering-signal level was then increased from a low value until the subject considered that each of the following three grades had been reached:

Just perceptible	(JP)
Perceptible	(P)
Disturbing	(D)

and the corresponding protection ratios were recorded. Tests were carried out with the five arrangements shown in Fig. 11; any other arrangement is related by symmetry to one of these. Unfortunately, it was not possible to carry out all the measurements as a complete factorial experiment and so the measurements had to be split up into smaller experiments.

Considering only the first four arrangements shown in Fig. 11 it was found that the only factors which affect the results are the nature of the wanted and interfering programmes and the subjects. The possibility of the modulation systems affecting the protection ratio can be found only by appropriate comparison of the three sets of results for the different system combinations. Assuming that factors apart from the programmes, subjects and systems combinations have no effect, the three sets may be combined for analysis. The results of this analysis show that certain types of wanted programme can mask the interference to quite a significant extent (up to 16 dB) while the protection required also depends on the type of programme on the interfering signal. Most variation among the subjects was found at the JP level. The most important result, however, is that the protection ratio was not significantly affected by the modulation systems and thus the results for the different channel arrangements may be put together to give a better estimate of the protection ratio required.

TABLE 1

GRADE OF INTERFERENCE	PROTECTION RATIO (dB)	STANDARD ERROR (dB)	STANDARD DEVIATION (SUBJECTS) (dB)
Just perceptible	40·15	0·55	1·55
Perceptible	32·70	0·62	0·88
Disturbing	25·45	0·60	0·76

As protection ratios must, in general, cater for the most unfavourable condition, it will be assumed that the wanted modulation is speech and that the modulation of the interfering signal is orchestral music. Table 1 then shows the mean protection ratios measured for arrangements (*a*), (*b*), (*c*) and (*d*) in Fig. 11. The third column gives the Standard Error of the protection ratio and is a measure of the repeatability of the experiment; for example, if the experiment were repeated with the same subjects a very large number of times, one can be 95% confident that the mean result for JP interference would lie between 39·05 dB and 41·25 dB. The fourth column is a similar measure of the spread due to the subjects.

Considering now the channel arrangement shown in Fig. 11(*e*) it is evident that, if the listener tunes the receiver so that the carriers are in the middle of the pass-band, then the total interference should not differ in level from that already measured for the other arrangements. If the listener detunes towards the unsuppressed sideband of the wanted signal, however, reduction in the level of interference is expected. The experiment which measured this condition involved rather few measurements. The results indicate a small subjective improvement, but the magnitude cannot be regarded as very accurate. Further measurements would have been made with the appropriate detuning if the tuning experiments (Section 5) had shown that listeners would be able to gain this advantage. As already noted in Section 5.2, however, the subjects either would not or could not detune systematically in the correct direction and therefore the potential improvement was not investigated further.

7. ADJACENT-CHANNEL INTERFERENCE

As will become evident later, a large number of channel arrangements are possible when adjacent-channel interference is considered. In addition, the frequency spacings between the wanted and interfering carriers normally range from 5 kc/s in the h.f. band to 10 kc/s in some broadcasting areas for the m.f. band, but measurements were carried out mainly at 9 kc/s because the effort available was limited. 9 kc/s is the spacing of the planned frequencies in the l.f. band and most of the m.f. band in the European Broadcasting Area.

The work was divided into three experiments which dealt respectively with c.s.s.b. to c.s.s.b. interference, c.s.s.b. to d.s.b. interference (and vice versa) and d.s.b. to d.s.b. interference. The procedure in these three experiments (described in Section 7.1) was similar to that for the co-channel experiments, the subjects being asked to say when the interference reached specific grades as the ratio of the signal levels was varied.

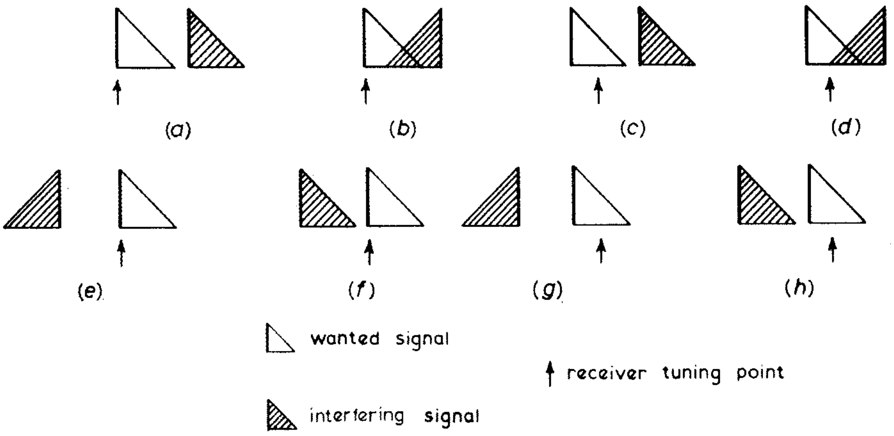

Fig. 12 - Eight possible arrangements for c.s.s.b.-to-c.s.s.b. adjacent-channel interference

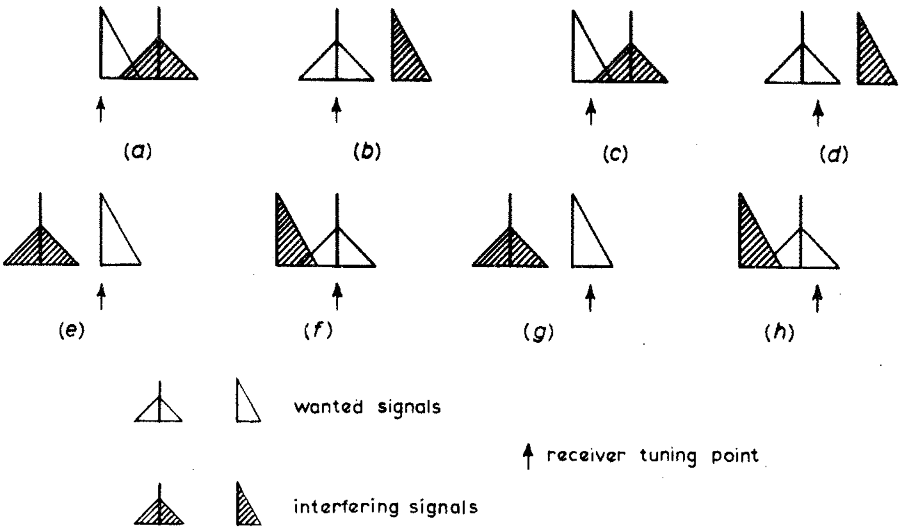

Fig. 13 - Eight channel arrangements measured for c.s.s.b./d.s.b. adjacent-channel interference

7.1. Measurement of Adjacent-Channel Protection Ratios

Fig. 12 shows eight channel arrangements possible for adjacent-channel interference with two c.s.s.b. signals. Assuming that the response in the r.f. and i.f. portions of the receiver is symmetrical and that interference is caused substantially by the same mechanism whether or not the wanted carrier is modulated, arrangement 12(*a*) should give the same result as 12(*e*) while 12(*b*) should give the same result as 12(*f*), but all were measured to facilitate analysis of the results. Likewise, in Fig. 13, which shows the c.s.s.b./d.s.b. adjacent-channel arrangements which were measured, arrangement 13(*a*) should give the same result as 13(*e*) while 13(*c*) should give the same result as 13(*g*). Finally in the d.s.b. to d.s.b. tests shown in Fig. 14, 14(*a*) and 14(*c*) should give the same result.

When the wanted signal was c.s.s.b., it was always an upper-sideband signal and thus, when necessary, the receiver was tuned to +3 kc/s with respect to the maximum carrier point. When the wanted signal was d.s.b., the receiver could have been detuned in either direction but it was decided to detune the receiver by +3 kc/s (that is the detuning which would have been used if the signal had been c.s.s.b.) because this gives a more direct comparison between the two systems.

In comparing the results of these three experiments it should be noted that the transistor receiver used in the first experiment became unavailable and was not used in the second experiment. The transistor receiver used in the third experiment, although the same model, was a different sample.

Before considering the differences between the modulation systems it may first be noted that over the range of signal levels considered (100 μV to 10 mV) the protection ratio is substantially unaffected by the wanted signal level. Unlike the case of co-channel interference, the nature of the wanted programme was not important, while changing the unwanted programme had little effect until the interference level was high. The difference between the two types of receiver was very marked unless the tone control on the valve receiver was turned to minimum in which case the behaviour of receivers was similar.

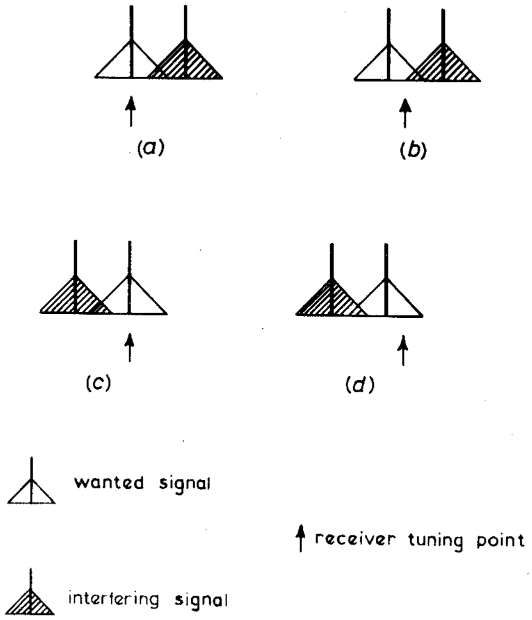

Fig. 14 - Four channel arrangements measured for d.s.b.-to-d.s.b. adjacent-channel interference

Overall analysis of the results is greatly simplified by comparing those configurations in which the only difference was the modulation system of the wanted signal. For example, the arrangement shown in Fig. 13(*a*) was compared with that in 14(*a*), 13(*c*) with 14(*b*) and so on. It was found that changing the modulation system of the wanted signal made no significant difference to the protection ratio and that this result did not depend on any of the other factors tested. As a result of this it was expected that the effect of detuning would not depend on the modulation systems and that dividing the mean change of protection ratio by the detuning in kc/s would give a measure of the slope of the sides of the i.f. amplifier. The results obtained are shown in Table 2 from the last two lines of which it can be seen that the agreement is within the limits of experimental error.

TABLE 2

RECEIVER	SLOPE (i.f.) (SUBJECTIVE TESTS)	STANDARD ERROR OF SUBJECTIVE MEASUREMENT	SLOPE (i.f.) (OBJECTIVE TESTS)
Transistor (No. 1)	4·5 dB/kc/s	0·8 dB/kc/s	-
Transistor (No. 2)	5·0 dB/kc/s	0·8 dB/kc/s	6 dB/kc/s
Valve	4·0 dB/kc/s	0·2 dB/kc/s	4 dB/kc/s

Having established that the modulation system of the wanted signal is unimportant and that the effect of detuning the receiver by 3 kc/s is largely predictable irrespective of the system of either signal, all the results may be combined in order to determine how the modulation system of the interfering signal affects the protection ratio. The analysis then shows that, when an interfering d.s.b. signal is replaced by an interfering c.s.s.b. signal "facing in" as shown in Fig. 15(*a*), the protection ratio is increased by the following amounts (with Standard Errors, S.E.):

Just perceptible	4·3 dB	S.E. 0·8 dB
Perceptible	5·5 dB	S.E. 0·7 dB
Disturbing	6·5 dB	S.E. 0·8 dB

If disturbance is caused only by lower-frequency sideband of the interfering signal, a difference of about 6 dB would be expected, corresponding to the increased sideband power density with c.s.s.b. The figures agree with this except when the interference is slight; some of the subjective disturbance must then be caused by other effects - presumably the "carrier whistle" corresponding to the fixed 9 kc/s "beat" between the carriers. The above figures did not significantly depend on the receiver.

When, however, the situation shown in Fig. 15(*b*) was considered, a marked difference between the receivers was found. Changing from c.s.s.b. "facing out" to d.s.b. did not affect the protection ratio for the valve receiver but increased the protection ratio by about 4 dB for the transistor receiver.

With the power density in the lower sideband of the interfering signal varying from that for a d.s.b. signal down to a very low value, the 9 kc/s carrier whistle was evidently causing relatively greater disturbance than before, and tended to be a dominant cause of interference with the valve receiver. Close inspection of the measurements showed that when the interfering signal was c.s.s.b. and "facing out" the measurements were much less repeatable. It appeared that the subjects listened either to the carrier whistle or to the sideband splash to the exclusion of the other but that they were most inconsistent in the way they did this. Thus these measurements do not provide a reliable measure of the effect of using a "facing out" c.s.s.b. signal.

As the success of a c.s.s.b. system depends almost entirely on making a large improvement with this arrangement, a further experiment, described in the next section, was carried out to investigate this condition more accurately.

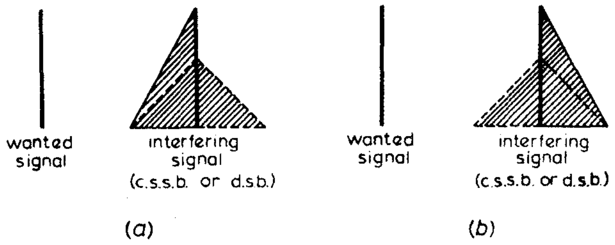
wanted signal
interfering signal (c.s.s.b. or d.s.b.)
wanted signal
interfering signal (c.s.s.b. or d.s.b.)
(a)
(b)

Fig. 15 - Comparison between c.s.s.b. and d.s.b. for adjacent-channel interference

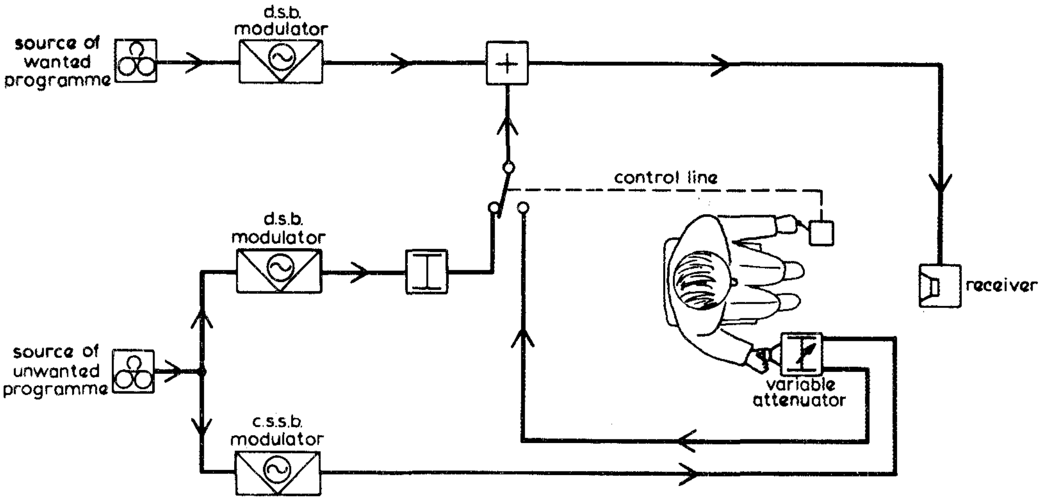

Fig. 16 - Arrangement for direct comparison between c.s.s.b. and d.s.b.

7.2. A Direct Comparison Between D.S.B. and C.S.S.B. as Interfering Signals

Fig. 16 shows the arrangement used for the fourth adjacent-channel experiment. Each subject was asked to adjust the attenuator controlling the c.s.s.b. signal until the interferences caused by the two unwanted signals sounded equally disturbing. The results are shown in Table 3.

TABLE 3

Reduction in protection ratio when d.s.b. is replaced by c.s.s.b. as shown in Fig. 15(b)

RECEIVER	LOW INTERFERENCE (JUST PERCEPTIBLE)	MODERATE INTERFERENCE (PERCEPTIBLE)	STANDARD ERROR
Transistor	12·2 dB	11·2 dB	0·5 dB
Valve	1·9 dB	4·0 dB	0·6 dB

The better overall a.f. response in the case of the valve receiver presumably causes the carrier whistle to be troublesome and restrict the improvement, whereas a considerable improvement over d.s.b. is obtained with the transistor receiver.

8. COMPARISON OF C.S.S.B. AND D.S.B. UNDER FADING CONDITIONS

It has been claimed[2] that c.s.s.b. will be less vulnerable to selective fading than d.s.b. and that consequently improved reception will be possible in fading conditions. There has been no experimental evidence that supports this claim, so subjective tests were carried out in the laboratory using a fading simulator.

The arrangement shown in Fig. 17 was used where the key held by the subject provided an instantaneous change from one modulation system to the other. The subjects were not told which modulation systems corresponded with the key positions and in addition the positions were interchanged according to a "random" sequence.

It was evident from preliminary tests that there is very little difference between the systems (c.s.s.b. and d.s.b.) and consequently the subjects were merely asked to say which position of the key (if either) gave the best reception. Plus one was scored when c.s.s.b. was preferred, minus one when d.s.b. was preferred and zero when neither was preferred. After each test the subjects (technical personnel) were asked for comments. All agreed that any differences were marginal and that although there was often a difference in the character of the distortion, on many occasions neither was to be preferred.

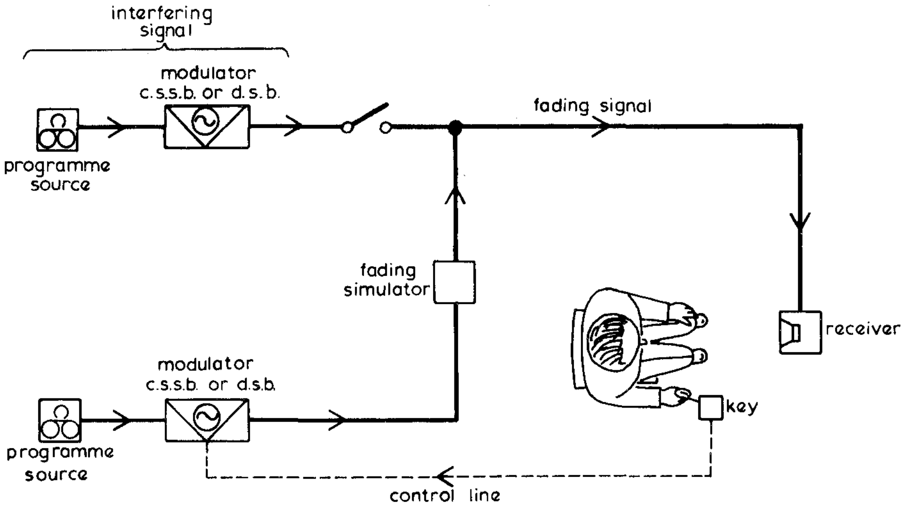

Fig. 17 - Experimental arrangement for fading tests

In carrying out these experiments it was noted that the subjects delayed making a choice between the systems until the distortion was particularly bad.

There are two main types of fading signal: first, that corresponding to reception of medium frequencies at the edge of the ground wave service area and secondly, that corresponding to reception of high frequencies over large distances. Both types of fading were simulated and the results are presented in the following sections.

8.1. M.F. Fading

Fig. 18 shows a block diagram of the arrangement used in the fading simulator for m.f. fading. The three oscillators producing the "sky wave" were arranged to beat slowly together and the overall fading rate was controlled by varying the frequency between their resultant and the fourth oscillator. The effects of seven factors were measured in each experiment and, because all the effects to be measured were small, second- and higher-order interactions were neglected. Thus, only eight conditions, that is one sixteenth of the total, were measured.

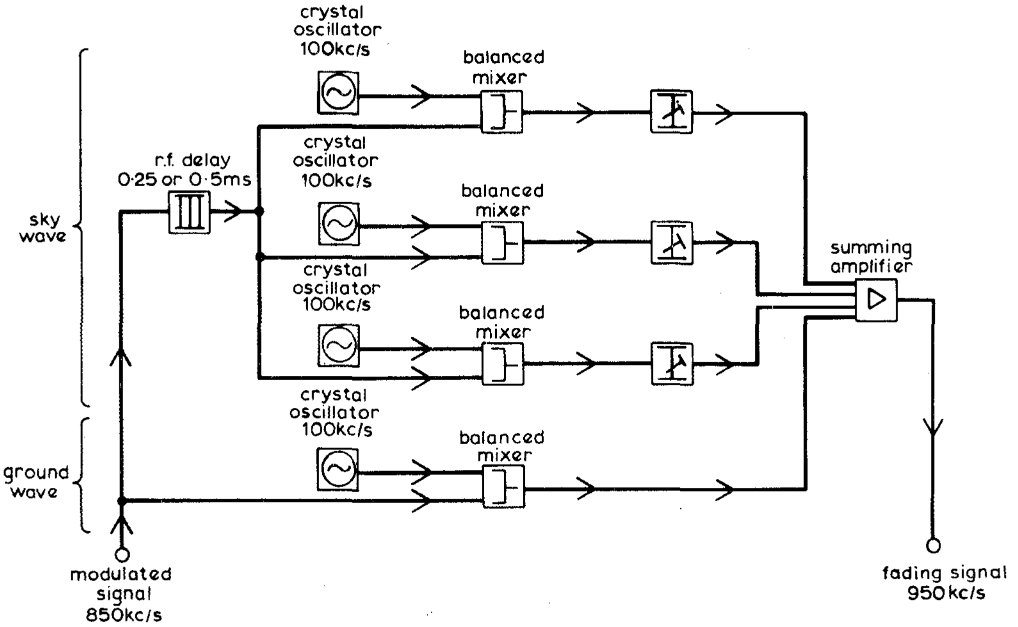

Fig. 18 - Block diagram of simulator for m.f. fading

(NOTE: The independent 100 kc/s crystal oscillators are adjusted to closely equal frequencies depending on required fading rate)

The results of the first experiment showed that there is a slight preference for d.s.b. at moderate signal levels, a slight preference for c.s.s.b. at low signal strengths, and that the type of receiver, receiver tuning point, programme fading rate, fading depth and sky wave delay do not affect this result. Closer inspection of the measurements showed that one of the subjects consistently scored plus one and that his results were different from all the others. When asked to comment at the end of the experiment he stated that the distortion was equally disturbing for each type of modulation but that he chose the signal with the better high frequency response. When the observations of this subject were excluded, the experiment showed a slight overall preference for d.s.b. unaffected by any of the factors tested.

A second experiment was performed in which the opportunity was taken to check the effects of the tone control, an interfering signal and audio compression. On this occasion none of the factors (including signal strength) affected the result and a small but significant overall preference for d.s.b. was shown. On average, then, it may be taken that there is little or no difference between the performance of the two systems under m.f. fading conditions; if there is a difference, the indications are that there would be a slight preference for d.s.b.

8.2. H.F. Fading

Fig. 19 shows a block diagram of the arrangement used in the fading simulator for h.f. fading. The simple situation is treated where two paths (say one two-hop and one three-hop) exist between the transmitter and receiver, the relative delay being 2 ms. Strictly speaking the final carrier frequency should have been in the h.f. band but it was felt that the results would not be significantly changed if the experiments were carried out at 950 kc/s.

Seven factors were varied and one eighth of the total conditions were measured, thus permitting evaluation of some of the second-order factors. The results may be summarized as follows. The fading rate, type of receiver, signal strength, presence or absence of interference and programme did not significantly affect the subject's choice. With no audio compression, neither system was preferred but when audio compression was put in, there was a significant preference for d.s.b. which was slightly less marked when the receiver was detuned. It may be noted that more compression was used in this experiment than in the corresponding m.f. experiment because it is customary to do so over h.f. circuits. It seems likely that the higher average modulation depth made the effects of carrier loss more disagreeable and under these conditions the subjects appear to have a very slight preference for d.s.b.

9. COMPARISON WITH FIELD TESTS

Full scale trials of c.s.s.b. have been conducted at h.f. using the same type of modulator unit as that used in the laboratory tests, full details being given in a separate report.[5] A brief summary of the main features of the trials and the conclusions will be given for the purposes of comparison.

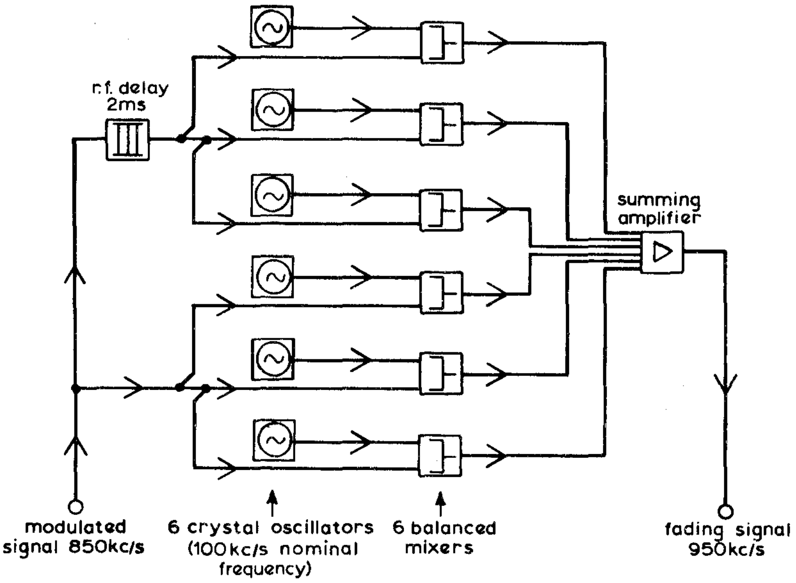

Fig. 19 - Block diagram of simulator for h.f. fading

The transmitter used for the tests was of recent design, with overall negative feedback and preset motorized tuning. No great difficulty was experienced in setting up c.s.s.b. and a sideband suppression of about 30 dB at 40% modulation depth was maintained with only slight day-to-day adjustment. It may be noted that when not used for the c.s.s.b. tests (which lasted for three hours per day), the transmitter was regularly retuned to other frequencies for other services (using d.s.b.) and thus the operating conditions were quite severe. At m.f., transmitters are generally run at fixed frequencies and so the stability should be even better than at h.f.

Most of the transmissions were from Rampisham (U.K.) to Singapore (path length 10,800 km) and the frequencies were 21·68 and 18·15 Mc/s. The signal received at Singapore was assessed subjectively by the station staff. In addition, tape recordings were made of the detected audio signal and these were returned to the United Kingdom for assessment.

As a result of the field trials it was concluded that there is no significant difference between c.s.s.b. and d.s.b. as the wanted signal, either when strong or when subject to fading conditions. This is in general agreement with the results of the laboratory tests.

10. DISCUSSION

Despite the comprehensive nature of the tests described in the preceding sections, the investigation was limited in a number of important ways. Thus, only one method of producing a c.s.s.b. wave was investigated. This method, the "squaring method", is not perfect but it is sufficiently near the ideal for practical purposes. It was found that the performance of the system was limited mainly by the characteristics of the receivers and, as only two were tested, it is necessary to consider what would happen with other receivers. Sufficient evidence was gained in the tests to assess this aspect which is discussed in more detail in the following sections.

10.1. Audio Quality

With the receivers tested, the increased audio distortion with c.s.s.b. outweighed the advantage of greater audio bandwidth irrespective of the tuning point and it seems likely that the same would be true for receivers with wider i.f. amplifiers. On the other hand, the same may not be true if the i.f. bandwidth is made too narrow because the degradation in quality and intelligibility due to the lack of the high audio frequencies becomes very serious as the total bandwidth is made less than about 4 kc/s. Thus, if the i.f. bandwidth at -6 dB is 5 kc/s (or less) one would expect that c.s.s.b. detuned by about 2 kc/s would sound better than a.m. not detuned but not necessarily better than a.m. detuned by the same amount (2 kc/s). It is of interest to note that some engineers detune by a small amount on d.s.b. even with an i.f. bandwidth of about 7 kc/s. All these differences are marginal, however, and only appear when direct comparison can be made under the most favourable conditions. It may therefore be said, that, while c.s.s.b. does not provide significantly better overall quality than d.s.b., neither does it provide significantly worse quality; adoption or rejection must therefore be based on other considerations.

10.2. Co-Channel Interference

If it is possible to produce a plan for the m.f. band such that all the nearest pairs of co-channel stations are of the opposite "hand" then some advantage over d.s.b. in protection ratio is possible. About 4 dB improvement was found with the receivers tested, and the improvement is expected to be a little more with very selective receivers. This advantage depends entirely on the listeners' being able to detune consistently by about 1·5 kc/s in the correct direction. If it is assumed that every member of the public, as a result of special instructions, became twice as consistent as the subjects tested and also became able to tune on average to the optimum point, statistically about one in ten receivers would still have a tuning error of more than 1·1 kc/s and would lose most of the advantage possible with c.s.s.b.

10.3. Adjacent-Channel Interference

When adjacent-channel interference is present on one side of a wanted signal it was found that the listeners detuned their receivers away from the interference by the same amount whether the wanted signal was c.s.s.b. or d.s.b. This is not surprising when the differences in quality between the systems are so marginal. Therefore the tuning point of the receiver does not affect comparisons between the systems for adjacent-channel interference. Two situations must be considered regarding interference from a c.s.s.b. transmission: firstly, that where the transmitted sideband of the unwanted signal "faces in" as shown in Fig. 15(*a*) and secondly, that where the unwanted signal "faces out" as shown in Fig. 15(*b*).

In the first case there is a degradation, by comparison with interference from a d.s.b. transmission, of about 5 dB, largely independent of the receiver and the listener. In the second case there is an improvement, the degree of which depends critically on the receiver and to a lesser extent on the listener. The greatest advantage is obtained with receivers which have poor audio frequency responses at 9 kc/s and also, presumably, with listeners who are relatively insensitive to this frequency. Adoption of c.s.s.b. therefore depends on a sufficient number of the population having suitable receivers. The most popular receiver is the portable transistor radio which tends to have the most favourable type of response for c.s.s.b. but these receivers are used extensively by young people who are much more sensitive to 9 kc/s.

It can be seen from these considerations that, although the improvement found for the transistor receiver (12 dB) provides an indication of the potential benefits of c.s.s.b., it cannot be used for planning a service because the tests did not cover enough receivers nor enough subjects. Before carrying out further tests, however, it is necessary to decide what performance the receivers should have (particularly with respect to the audio output at 9 kc/s) and how many receivers meet this specification. A further complication is that the potential c.s.s.b. improvement varies considerably from one subject to another and it will be necessary to ensure that the subjects tested are representative of the population to be served.

10.4. Receiver Tone Controls

So far the discussion has been in terms of receivers with fixed overall selectivity but many receivers are provided with tone controls which provide, in effect, a measure of variable selectivity. As these controls are generally fitted to receivers with good audio response it means that, if turned to minimum when adjacent-channel interference is present, the situation is more favourable than that considered in Section 7.2 and thus the c.s.s.b. improvement will be nearer 12 dB than the 2 to 4 dB measured with the good quality receiver. It was noted during the tuning tests that the non-technical subjects usually turned the control to minimum on the first occasion when adjacent-channel interference was present and thereafter left the control in this position.

11. CONCLUSION

The performance of a method of generating c.s.s.b. signals has been investigated under practical conditions and it was found that the transmitted signal is a good approximation to a true c.s.s.b. signal. Typical domestic receivers were used in laboratory tests simulating a wide range of reception conditions. The results showed that, for the most part, c.s.s.b. is neither better nor worse than conventional d.s.b. The only significant advantage occurs under conditions of adjacent channel interference. A c.s.s.b. signal can then cause about 12 dB less interference (than d.s.b.) to the adjacent channel on one side but about 5 dB more interference to the adjacent channel on the other side. It is therefore doubtful if there is any overall advantage but this can only be assessed in conjunction with specific plans and frequency allocations.

12. ACKNOWLEDGEMENTS

The c.s.s.b. adapters used in the experiments were kindly loaned to the BBC by N.V. Philips, Eindhoven and I would like to thank Dr. Stumpers and Mr. T.J. van Kessel for the very helpful discussions which took place during the course of the investigation.

13. REFERENCES

1. KAHN, L.R., 1957, A compatible single-sideband system designed for use in the broadcast service, I.R.E. Natn. Conv. Rec., 1957, **5**, 7, pp. 11 - 15.
2. KAHN, L.R., 1961, Compatible single-sideband, Proc. Inst. Radio Engrs., 1961, **49**, 10, pp. 1503 - 1527.
3. VAN KESSEL, T.J., STUMPERS, F.L.H.M. and UYEN, J.M.A., 1962, A method for obtaining compatible single-sideband modulation, EBU Rev., 1962, **71A**, pp. 12 - 19.
4. VAN KESSEL, T.J., 1964, Compatible single-sideband modulation, Philips tech. Rev., 1963/64, **25**, 11/12, pp. 311 - 319.
5. Compatible single-sideband modulation : comparisons with double-sideband modulation over high-frequency circuits, Research Department Report No. E-116, Serial No. 1965/48.
6. MORONEY, M.J., 1956, Facts from figures, London, Penguin, 1956.
7. WILSON, E.B., 1952, An introduction to scientific research, New York, McGraw-Hill, 1952.
8. FISHER, R.A., 1951, The design of experiments, 6th ed. Edinburgh, Oliver and Boyd, 1951.
9. HARWOOD, H.D., Apparatus for measurement of non-linear distortion as a continuous function of frequency, BBC Engng. Monogr. 49, 1963.

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